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Final Technical Report
December 1977

IMPROVED DUAL-MODE ELECTRON GUN

Fredrik Bjornstad

Varian Associates, Incorporated

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An advanced non-intercepting gridded gun was designed, fabricated, and preliminary tested.

The use of magnetic flux in the cathode region preserves the beam diameter when the grid voltage is reduced for a lower power mode of operation. This will result in a more stable TWT performance, since the gain difference associated with the two modes is significantly reduced.

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EVALUATION

This task demonstrated the feasibility of confined flow focusing in PPM traveling wave tubes and contributed to the performance of advance design traveling wave tubes. The program has direct application to TPO 4B. Information derived from this program will find use in systems requiring advanced ECM and ECCM capability. The intended application of the information obtained will be to achieve optimum design parameters in systems having high pulse up capability. The two gun design developed will be used as a starting point for any future procurements which have similar design goals.

Ronald Vandivier
RONALD VANDIVIER
Proj Engr/OCTP

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PREFACE

This report was prepared by the Palo Alto Microwave Tube Division, Varian Associates, Inc., Palo Alto, California for Air Force Contract F30602-76-C-0177 under Rome Air Development sponsorship. This is a final report covering the period from 1 April 1976 to 31 September 1977. The Rome Air Development Center project Engineer is Mr. Ronald W. Vandivier (OCTP).

SUMMARY

The design approach chosen for the electron guns in this study involves the use of partial magnetic flux threading of the cathode. The magnetic flux threading of the cathode allows the use of higher magnetic focusing field and preserves the beam diameter between two modes of operation. The rms value of the periodic magnetic focusing field had to be limited to 1.35 times the brillouin value to avoid excess rotational energy of electrons at the beam edge in the field reversal regions.

Two gun types have been studied. One gun uses a single control grid and produces a solid beam in both the high and low current modes of operation. In the second gun, two control grids are used to produce a solid beam in the high current mode, and a hollow beam in the low current mode.

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1. INTRODUCTION

The objective of this program was to develop, fabricate and evaluate an advanced non-intercepting gridded gun design for dual-mode traveling wave (TWT) application. The program was expected to demonstrate that the performance objectives have been achieved by testing the electron beam in an actual TWT under rf drive.

In a traveling wave tube, the beam voltage is determined by the required synchronization between the electrons and the electromagnetic wave propagation on the circuit. Changes in the beam power for dual-mode operation must therefore be accomplished by changes in the beam current. The changes in the beam current also affect gain and efficiency. The electrostatic beam diameter produced by a gridded gun will decrease as the grid voltage is decreased for lower beam current. A reduction in the beam diameter will cause a reduction in the interaction impedance. Since gain is proportional to the one-third power of the interaction impedance, this will accentuate the gain difference between the two modes of operation, in addition to the decrease in the beam current.

The design approach chosen for this study involves the use of magnetic flux in the cathode region. The electron trajectories will tend to follow the magnetic flux lines. It can be seen from Figure 1 that with partial magnetic flux threading of the cathode the beam diameter is better preserved in the lower power mode. For a current pulse-up ratio of 3:1 and a magnetic focusing field of 1.35 times the brillouin field (B_{Br}) the ratio between mean diameters in the two modes is 0.89. It is desirable to keep the normalized average rotational energy to 0.1 or less. Figure 2 shows the restrictions placed on the amount of focusing field used to minimize the effect of high rotational energy in the field reversal region.

Two design approaches were chosen as a result of a small-signal gain analysis using different current density distributions in the beam. In one approach a solid beam is produced in the two modes of operation by using a single control grid. Magnetic flux threading of the cathode was used to minimize the reduction of the beam diameter between high- and low-current modes of operation.

In the second approach, two control grids are used to produce a solid beam in the high-current mode and a hollow beam in the low-current mode. The hollow beam is generated by elimination of current in the center core of the solid beam. Magnetic flux threading of the cathode will also be used for this gun in order to minimize the change of the outer diameter, and to prevent the collapse of the hollow low-current mode beam.

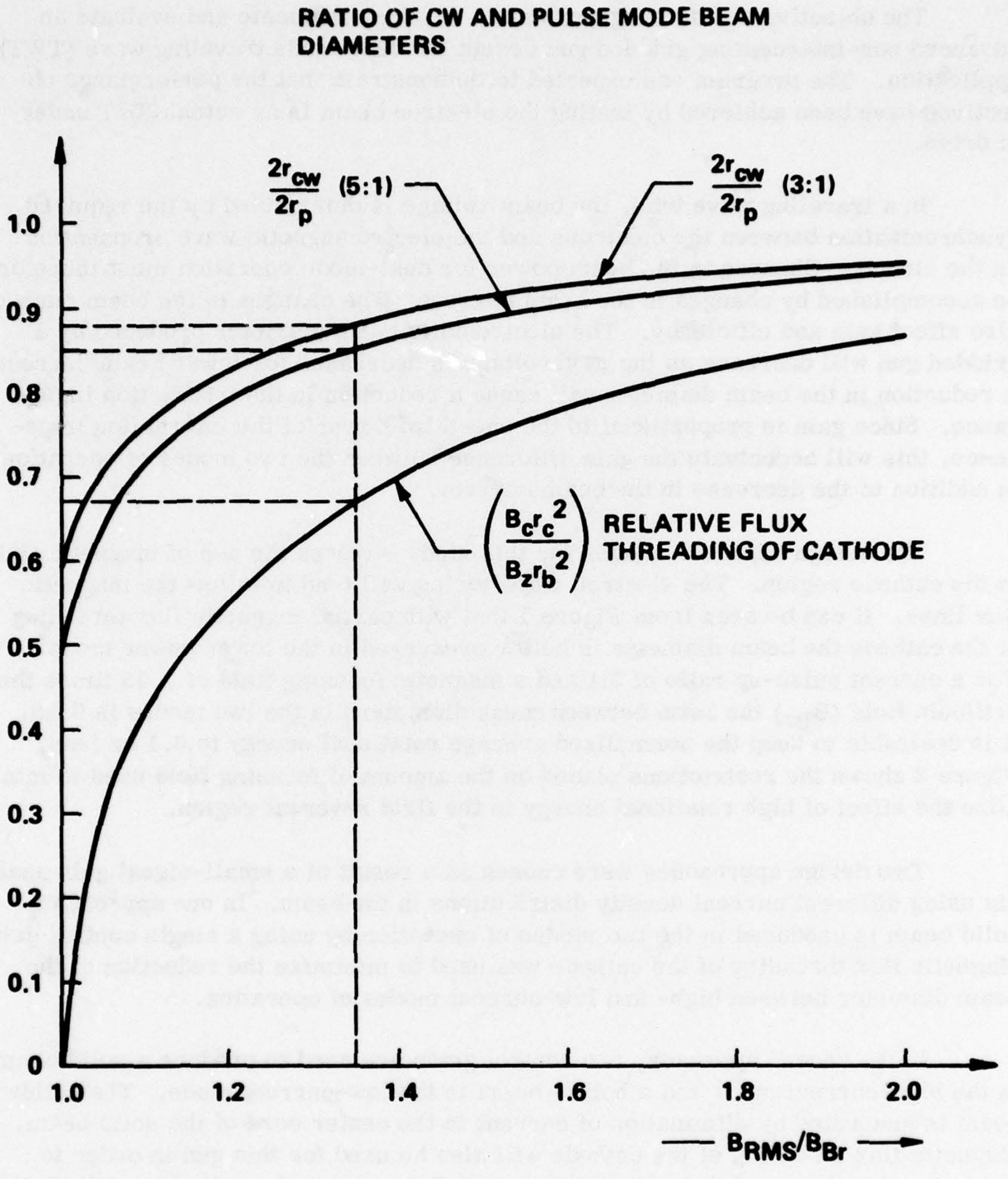

Figure 1. Relative Flux Threading of the Cathode, and Ratios of cw and Pulse Mode Beam Diameters vs the Ratio of the RMS Focusing Field and the Brillouin Field.

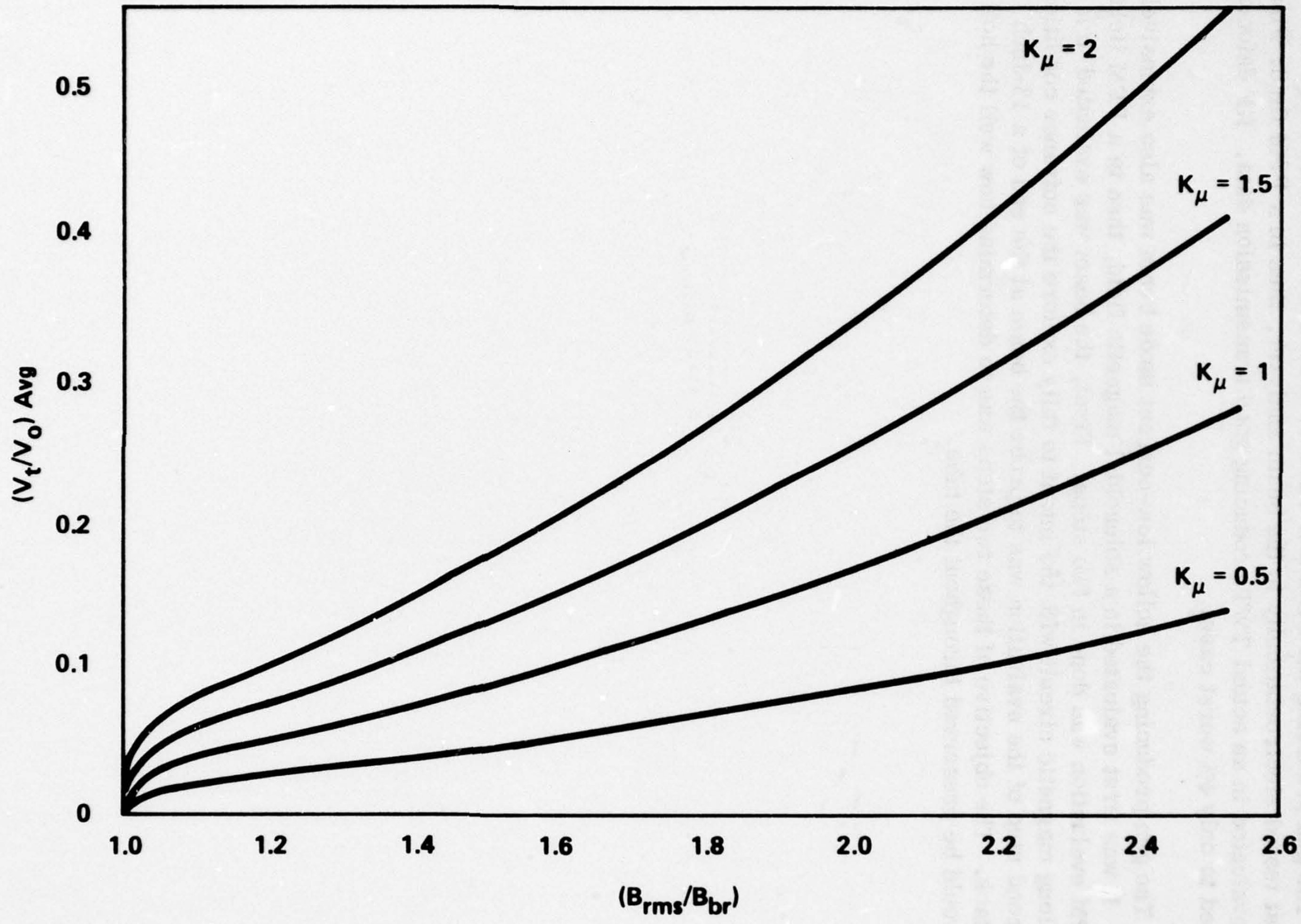

Figure 2. PPM Focused Solid Beam Normalized Average Energy of Edge Electrons vs the Ratio of the RMS Focusing Field and the Brillouin Field.

The gun producing the solid low-current mode beam was evaluated. It was first tested electrostatically in the beam analyzer, then in a PPM field. Finally, it was evaluated in an actual TWT producing good transmission data. RF defocusing amounted to only 4% worst case.

The gun producing the hollow low-current mode beam was also extensively tested. It was first evaluated in a solenoidal magnetic field, then in a PPM field. The PPM evaluation was done in two steps. First, the beam was evaluated in a 3-inch long magnetic circuit with the intent to fully explore the entrance conditions. The second step of the evaluation was to probe the beam at the end of a 13-inch long PPM stack. The objective of these two steps was to determine how well the hollow beam would be preserved throughout the tube.

2. SELECTION OF BEAM PARAMETERS

In order to determine the helix parameters, a small-signal computer program was used which takes into account the effect on the space-charge waves of flux threading the cathode. It was assumed that a nondispersive velocity characteristic could be obtained by suitably loading the helix with longitudinal vane segments attached to the inside of the barrel. From cold test data on similar circuits, it was determined how much the interaction impedance would be reduced by such loading. This reduction in the interaction impedance was taken into account in the calculations.

From several trials it was found that maximum gain flatness was obtained for a ratio of beam diameter to inside helix diameter of 0.6. It was also found that a uniform output helix would not give the required wideband efficiency, so the phase velocity was reduced near the end of the output helix. A 5 percent phase velocity step led to the most satisfactory small-signal gain performance.

Three cases were computed to show the effects of various approaches in beam design. First the case of no-flux through the cathode was analyzed. For comparison the computed small signal gain vs. frequency response is shown in Figure 3. Since the beam diameter varies by a factor of 1.7 between the low-current and high-current modes the change in gain is substantial. If the low-current mode gain were to be 30 dB minimum, the gain change would be about 52 dB at mid-band. The very high gains in the pulse mode would obviously result in stability problems, both from backward-wave oscillation and internal feedback. In addition, the gain variation over the band is about 20 dB in the high-current mode.

Next, if 67 percent of the magnetic flux in the beam is allowed to thread the cathode, the change in beam diameters between the low- and high-current modes is only 1.14. The small-signal gain characteristics are shown in Figure 4 for the case of both beams being solid. In this case, the difference in mid-band gain is 36 dB and the gain variation over the band is less than 13 dB, when the low current gain is 30 dB minimum.

Finally, a calculation was made considering the cw beam to be hollow. Results for this case are shown in Figure 5. Because of higher interaction impedance of the hollow beam, the gain change between modes is less than 25 dB, and the gain variation over the band is less than 11.5 dB. The gain is also nearly balanced at the band edges for both modes.

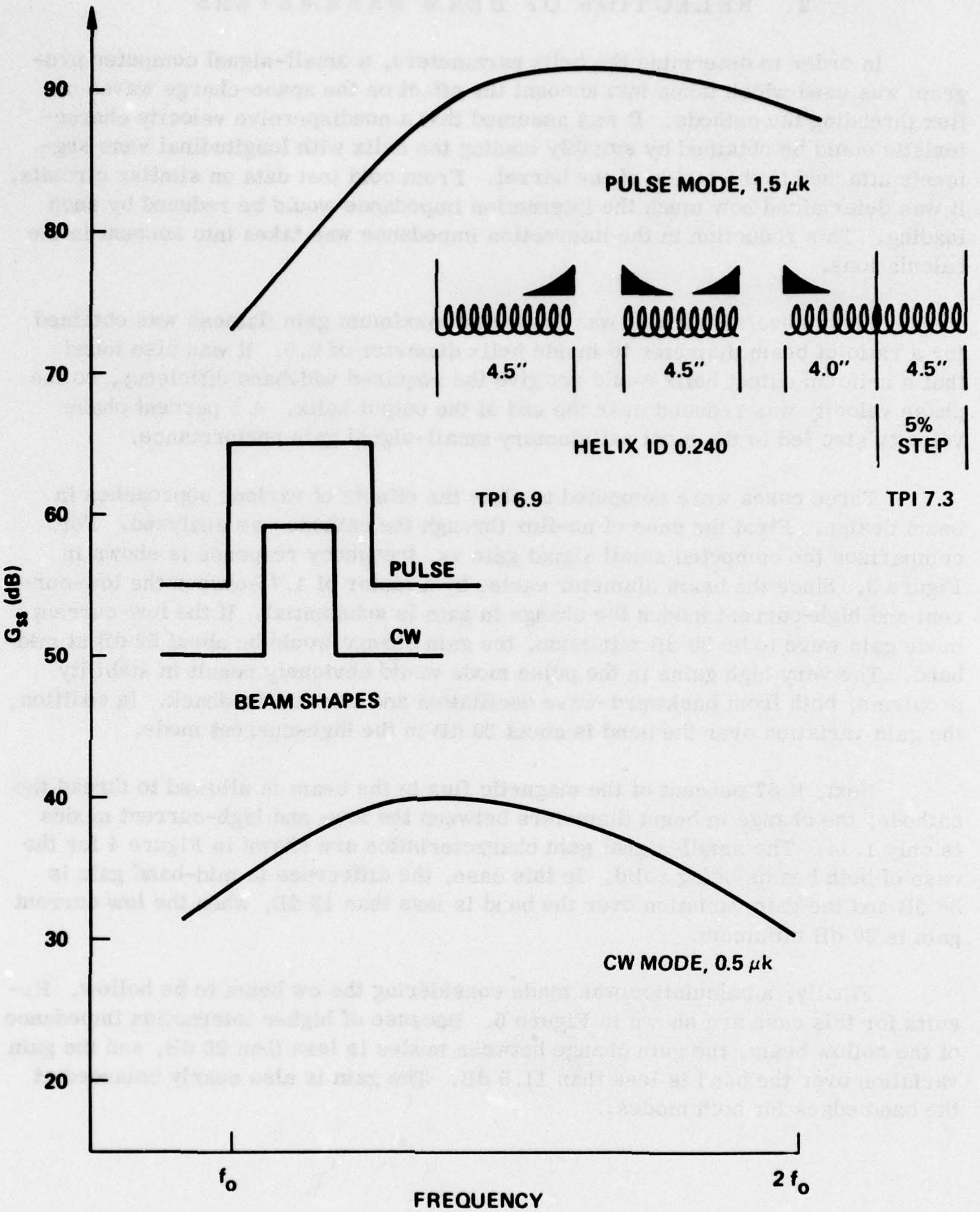

Figure 3. Small Signal Gain vs Frequency Response With Brillouin Focused Beams

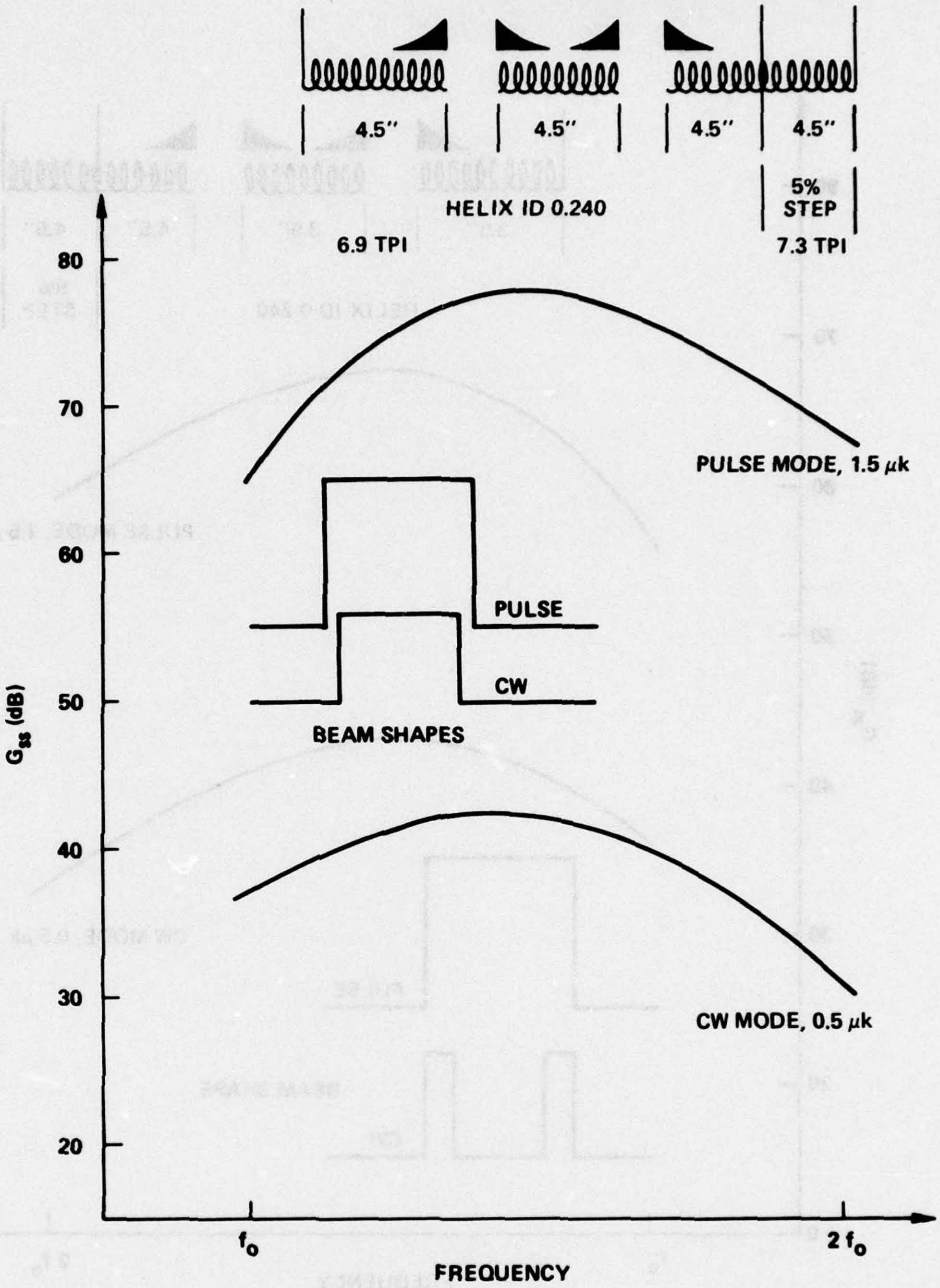

Figure 4. Small Signal Gain vs Frequency Response with Flux Threading of Cathode, cw Beam is Solid.

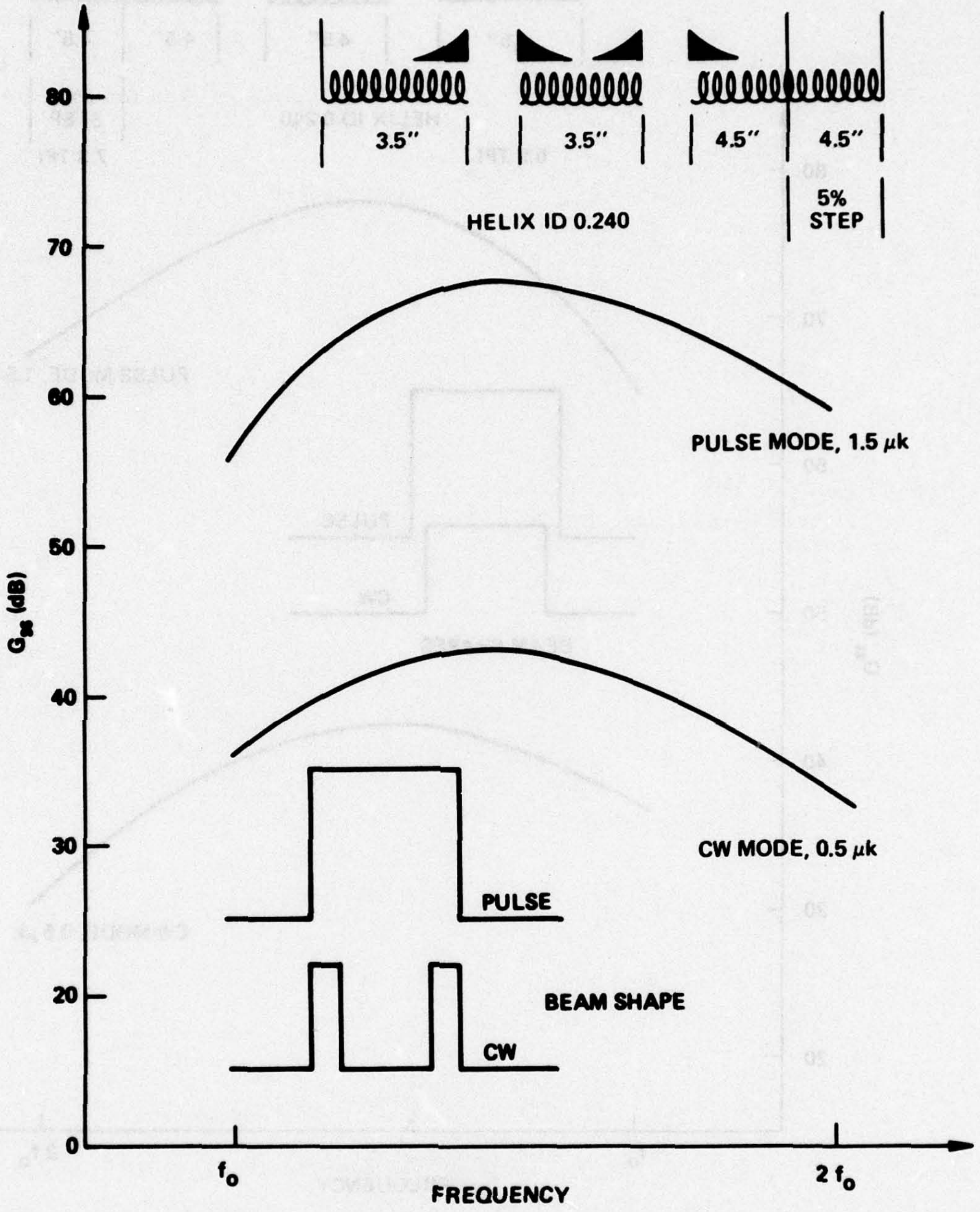

Figure 5. Small Signal vs Frequency Response with Flux Threading of Cathode, cw Beam is Hollow.

3. COMPUTER STUDY

3.1 DESIGN OF ELECTROSTATIC BEAM

A computer analysis was made using Varian's gun simulation program. For convenience in comparison of results the active cathode diameter was made to be equal to 1.0 inch. The electron beam was injected with uniform current density into the plane of the control grid with the appropriate currents for the two operating modes. The 15 reference electrons used in the analysis are launched perpendicular to the grid. Distortion in beam optics produced within the individual grid cells is neglected in this preliminary analysis. The formation of the beamlets within the individual grid cells was the subject of a separate computer study.

Three area convergences of 4:1, 6.5:1, and 10:1 in the high-current mode were selected for this analysis. The radius of curvature of the control grid was adjusted for good laminarity in the high-current mode. When the area convergence of the gun increased, the separation increased between the beam minimums for the two operating modes. This separation will increase the scalloping when the two operating beams are focused with the same magnetic field.

A detailed computer analysis was made to determine the proper grid cell geometry to minimize electron cross-over within the grid structure. Two control grids in addition to the focus grid are required, when the low-current mode beam is hollow. This case required a fairly extensive study. It showed that the formation of the beamlets within the grid cells is fairly sensitive to the grid thickness and to the spacing between the two control grids. In general, the smallest lens effect and the best optical performance is obtained for the smallest grid thickness and spacing. A grid thickness of 0.003 inch and a spacing of 0.005 inch was selected to assure mechanical rigidity.

When the beam was solid in the low-current mode, only one control grid was required. Beam distortion in this case was minimal.

3.2 RMS MAGNETIC FIELD ANALYSIS

As mentioned in the previous section, three area convergences were chosen for this analysis, 4:1, 6.5:1, and 10:1. To ensure a normalized rotational energy level of 0.1 or less, the selected RMS focusing field of the beam was 1.3 times the brillouin value. This requires that about 64 percent of the RMS magnetic flux in the beam threads the cathode. (See Figure 1.) The shaping of the magnetic field in the gun region was performed for minimal scalloping of the beam in the focusing region for the high-current mode. Preservation of the beam diameter in the low-current mode due to magnetic flux threading of the cathode resulted in a ratio of the high- to low-current mode beam diameter of 0.89. The ratio of the beam diameters under brillouin-focused condition was approximately 0.5.

As expected, the beam with the 4:1 area convergence had the least amount of scalloping in either operating mode. This beam was then selected for further investigation.

When the two operating beams were focused with the same magnetic field, it became apparent that optimizing both modes simultaneously was impossible and that some compromise in scalloping was necessary. A mapping of the beam performance was made for various magnetic slopes in the gun region. A compromise magnetic slope was derived producing equal maximum excursions of the beams for the two operating modes. This magnetic profile produced a scallop of 7% in the high-current mode and 22.5% in the low-current mode.

A similar analysis was performed when the low power mode beam was hollow. The resultant magnetic slope produced, in this case, 10% scallop.

3.3 PPM MAGNETIC FIELD ANALYSIS

A PPM magnetic field profile was constructed on the basis of the result in the RMS magnetic field study. The ratio of the plasma wavelength and magnet period was 3.1 for the high-current mode and 5.4 for the low-current mode which are acceptable values for good focusing. Figure 6 is a computer simulation of the high-current mode beam in a PPM field. Since the slope of the magnetic field in the gun area had been determined in the previous study, the only parameter varied was the length of the axial extension of the first half-period. The location of the first magnetic field reversal with respect to the beam minimum of the high-current mode was located. The effect of the variation in the axial extension of the first half-period was minimal. The scalloping of the outer edge electrons was low in all three cases. The high-current mode according to the computer prediction, was 6 percent scalloping. The solid low-current mode beam had 16 percent, and the hollow beam, 14 percent. The velocity spread between the outside and inside beam trajectory was also quite acceptable.

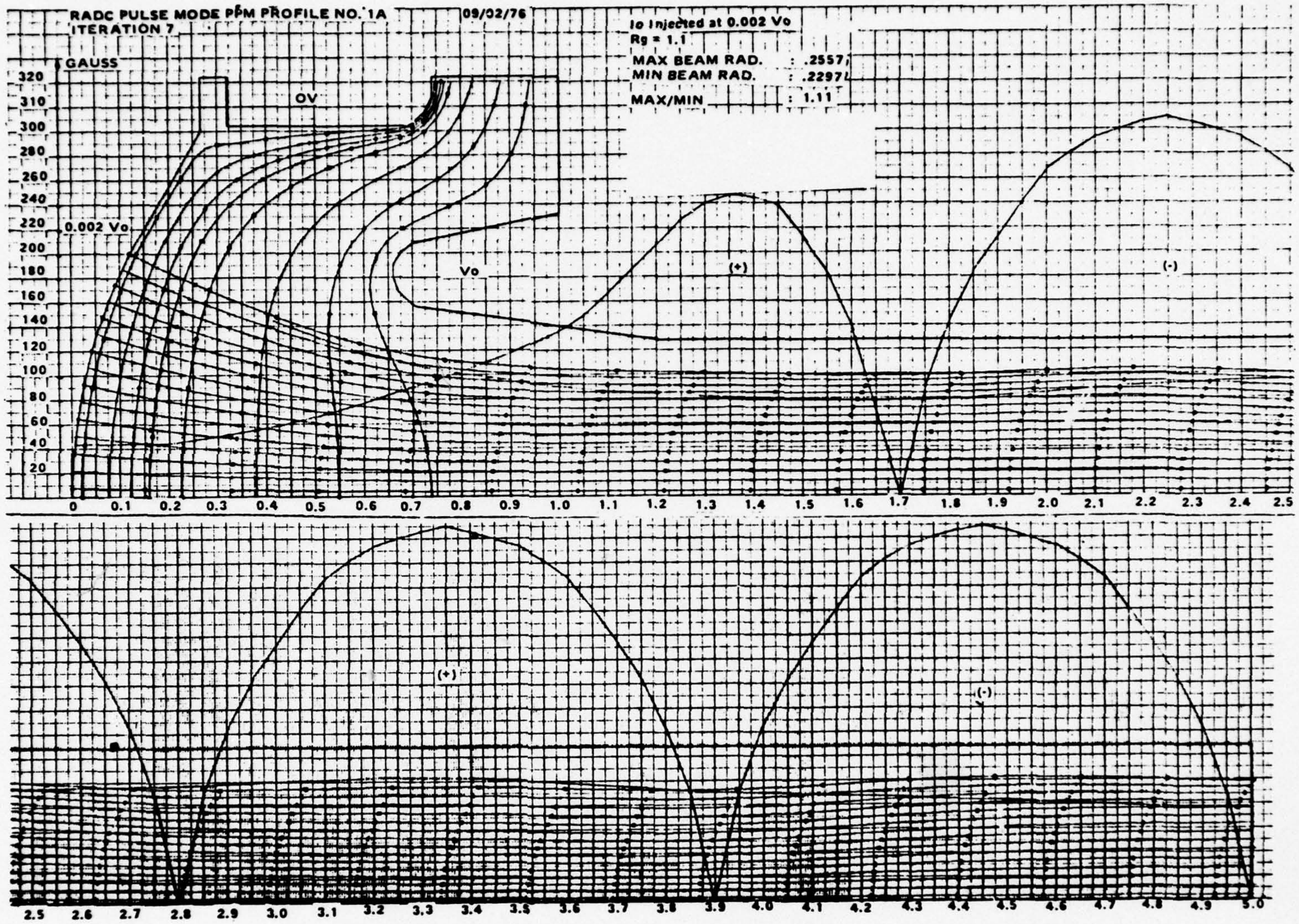

Figure 6. High-Current Mode Beam with PPM Magnetic Field

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4. MAGNETIC CIRCUIT DESIGN

A computer program solving LaPlace's equation was used to design the magnetic circuit needed for the PPM field. The design of the individual magnets and polepieces was made in accordance with Sterret and Heffner; "Design of Periodic Magnet Focusing Structures".[1] The design of the PPM focusing system is shown in Figure 7. The large hole diameter in the gun polepiece and the radially magnetized magnet are the principal elements providing the flux threading of the cathode region.

An actual magnetic circuit was designed based on this information. Experiments to duplicate the PPM goal curve were performed. With some minor correction, the goal was very nearly duplicated and the slope of the magnetic field in the cathode region matched fairly well. The axial extension of the first half-period was approximately 0.1 inch larger than originally planned. A flux tube measurement was made to confirm the flux line distribution through the gun region. The flux lines were in very good agreement with the computed trajectories for the high-current mode beam. A good correspondence between the two is required for minimal scalloping. This magnetic field was used in the gun simulation program to confirm the beam shape. The scalloping of the beam in both high- and low-current modes was acceptable.

A similar set of experiments were performed to derive the solenoidal field for the first step in the hollow beam study. The flux tube measurement again agreed well with the computed trajectories.

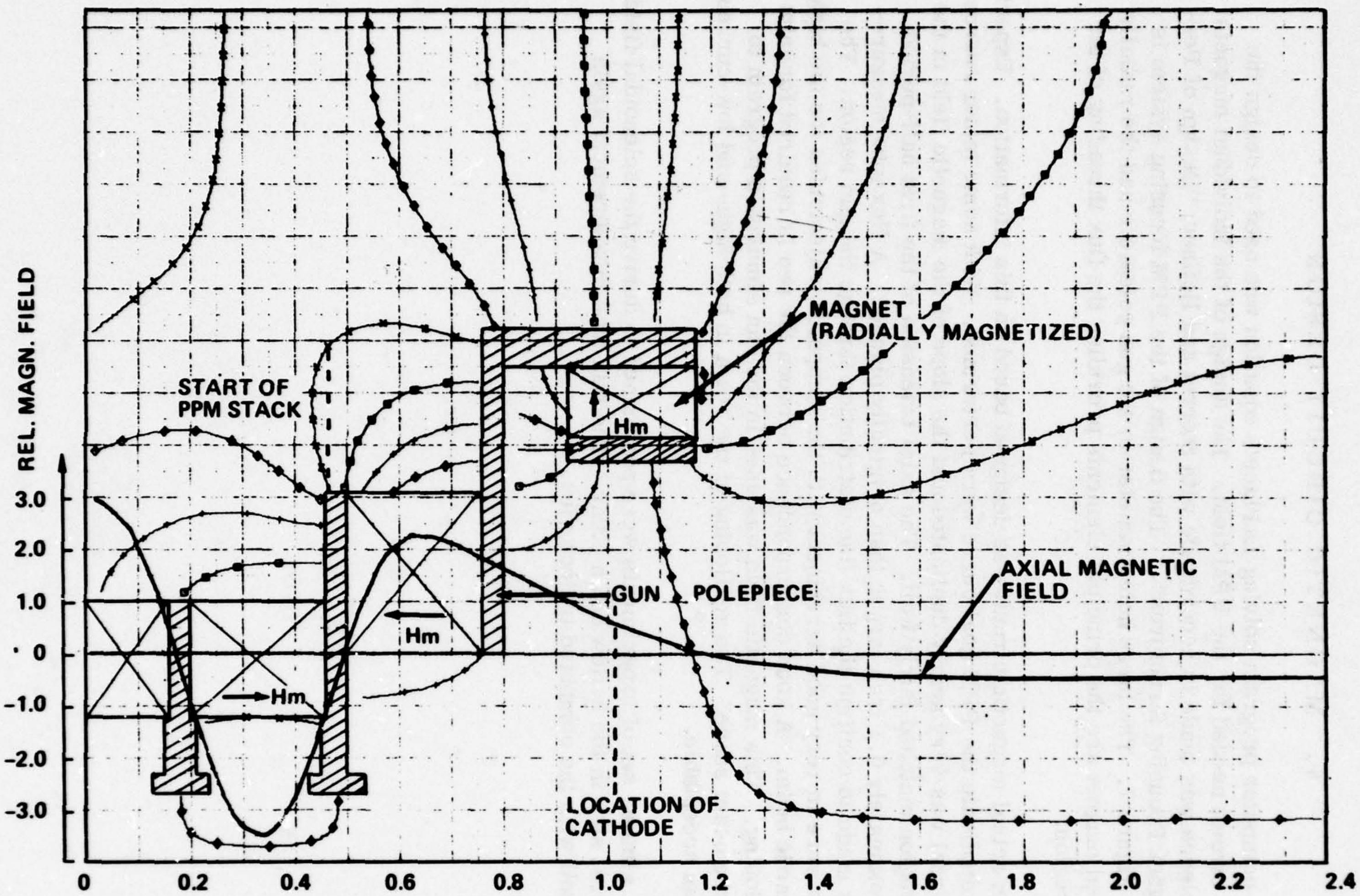

Figure 7. PPM Focusing System with Flux Threading of the Cathode

5. GUN STRUCTURE

5.1 GUN DESIGN FOR SOLID CW-MODE BEAM

There were no real problems in fabrication and assembly of the gun structure. As mentioned previously, the gun is a non-intercepting gridded gun. The gun contains two sets of grids with a transparency of 80 percent. The grid closest to the cathode operates at cathode potential and prevents electron emission from areas of the cathode covered by the grid vanes of both grids. The second grid is used for control of the beam current.

The first grid was placed directly in contact with the cathode and is operated at approximately cathode temperature. This eliminates the assembly problems associated with the close spacing between the cathode and shadow grid in the conventional non-intercepting gun. In addition, a significant improvement is obtained in the electron optical performance of the gun because the focusing grid operates at close to cathode temperature. Since electron emission must be inhibited from the grid vanes, the focus grid was coated with a thin layer of zirconium to inhibit grid emission.

5.2 GUN DESIGN FOR HOLLOW CW-MODE BEAM

The gun producing the hollow cw beam utilized the same high voltage structure as the one for the solid cw beam. This gun would require two control grids in addition to the focusing grid placed directly on the cathode. It was determined from the computer study that the formation of the beamlets within the grid cells is fairly sensitive to the grid thickness and the spacing between the two control grids.

The stability of the hollow beam was studied in a step-by-step approach. The hollow beam was first generated by a gun with a simple electrode configuration. The gun contained two grids, one focus grid and one control grid. The hollow beam was obtained by eliminating the emission from the center of the cathode. This configuration was used for evaluation of the hollow beam.

The complete gun for the hollow beam operation required one focus grid and two control grids. It was necessary to have a complex control grid configuration to properly screen the grid that was biased off in the low current mode operation. Several failures were experienced during the electron discharge machining of these control grids. Neither time nor money permitted new starts to be made. The study of this complete gun was consequently dropped.

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6. BEAM ANALYZER RESULTS

6.1 EVALUATION OF THE GUN PRODUCING A SOLID LOW-CURRENT MODE BEAM

6.1.1 Electrostatic Beam Results

The results of the electrostatic beam analysis were in fairly good agreement with the computer analysis. The beam analyzer showed a laminar beam profile with a minimum beam diameter of 0.132 inch in the high-current mode. The desired beam diameter is 0.130 inch. Test results are shown in Figures 8 through 10. Grid interception in the pulse mode, with 220 volts applied to the grid, was 3.6 mA, corresponding to 0.3 percent of the cathode current. The beam diameter for microperveance 0.5 was 0.065 inch.

The beam was also studied at microperveance 0.3, corresponding to a ratio in power of 10:1. As expected, the diameter ratio between the high-current and low-current mode was high. The beam diameter was 0.055 inch.

6.1.2 Confined-Flow Beam Results

Two evaluations were made of the beam in the PPM field. The first test revealed a spiraling beam. This was due to localized saturation of the iron polepiece outside the gun envelope by the radially magnetized samarium cobalt magnet. This magnet consists of six radially magnetized segments and is used for magnetic field shaping in the gun region. The strength of this magnet is adjusted by varying the number of magnet segments. It turned out that only one segment was needed to obtain the correct field variations on the axis. The polepiece saturated in the vicinity of the magnet, producing large asymmetry in the magnetic field and causing the electron beam to spiral.

The second evaluation of the electron beam was made with thicker iron surrounding the gun. This time the results were in fairly good agreement with the computer analysis.

The gun was tested at all three microperveances, 1.5, 0.5 and 0.3. The beam was laminar in all three cases. For a microperveance of 1.5, the beam diameter was 0.136 inch and the scalloping was 15.5%. The magnetic flux threading of the cathode preserved the beam diameter well when the gun was operated at lower perveances. The beam diameter for the 0.5 microperveance was 0.126 and the scalloping was 14.6%. The diameter ratio between the 0.5 μK beam and the 1.5 μK beam was 0.92. The microperveance 0.3 beam had a diameter of 0.122 inch; the scalloping for this case was 15.2%. Beam results are shown in Table 1.

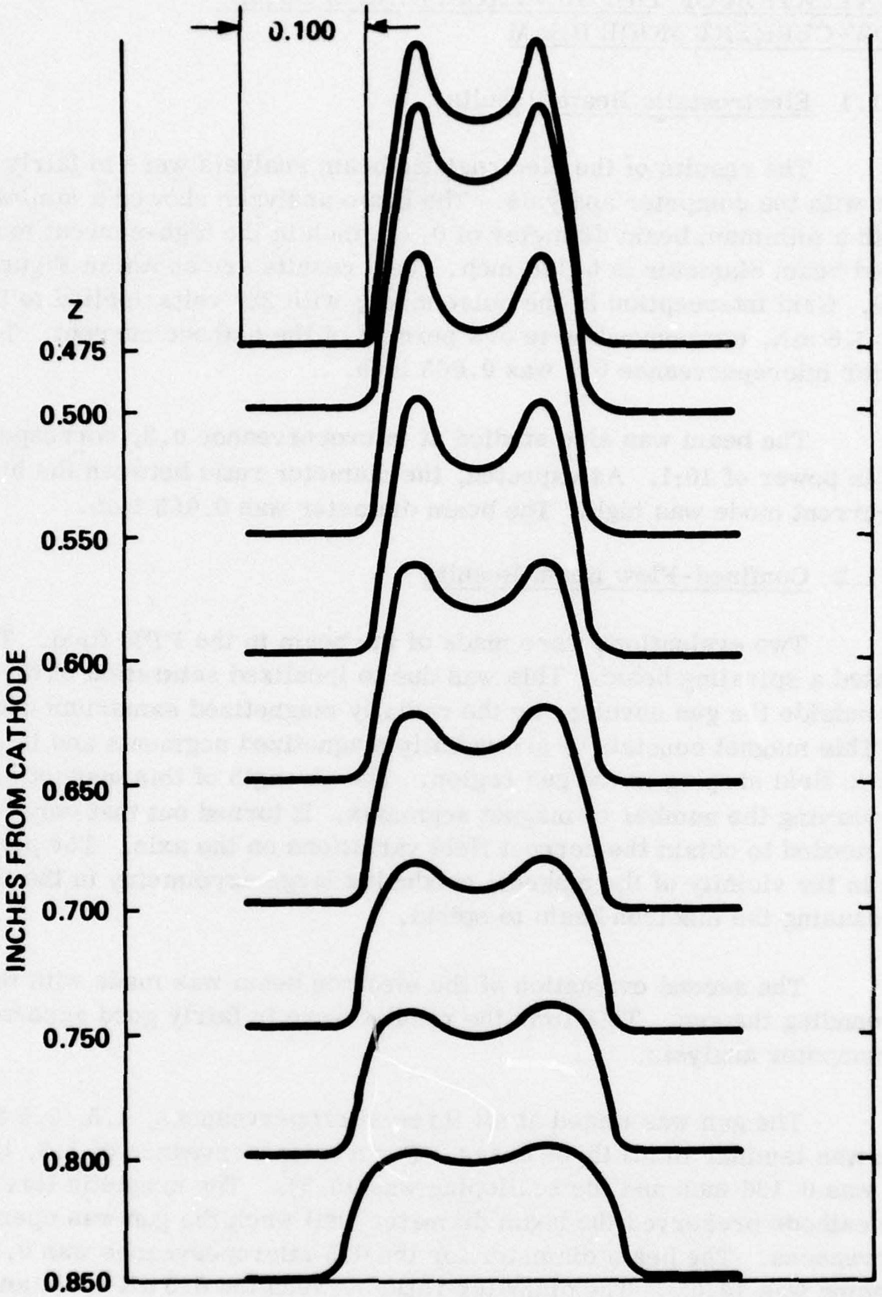

Figure 8. **Beam Analyzer Result of Electrostatic Beam - High-Current Mode ($\mu k = 1.5$).**

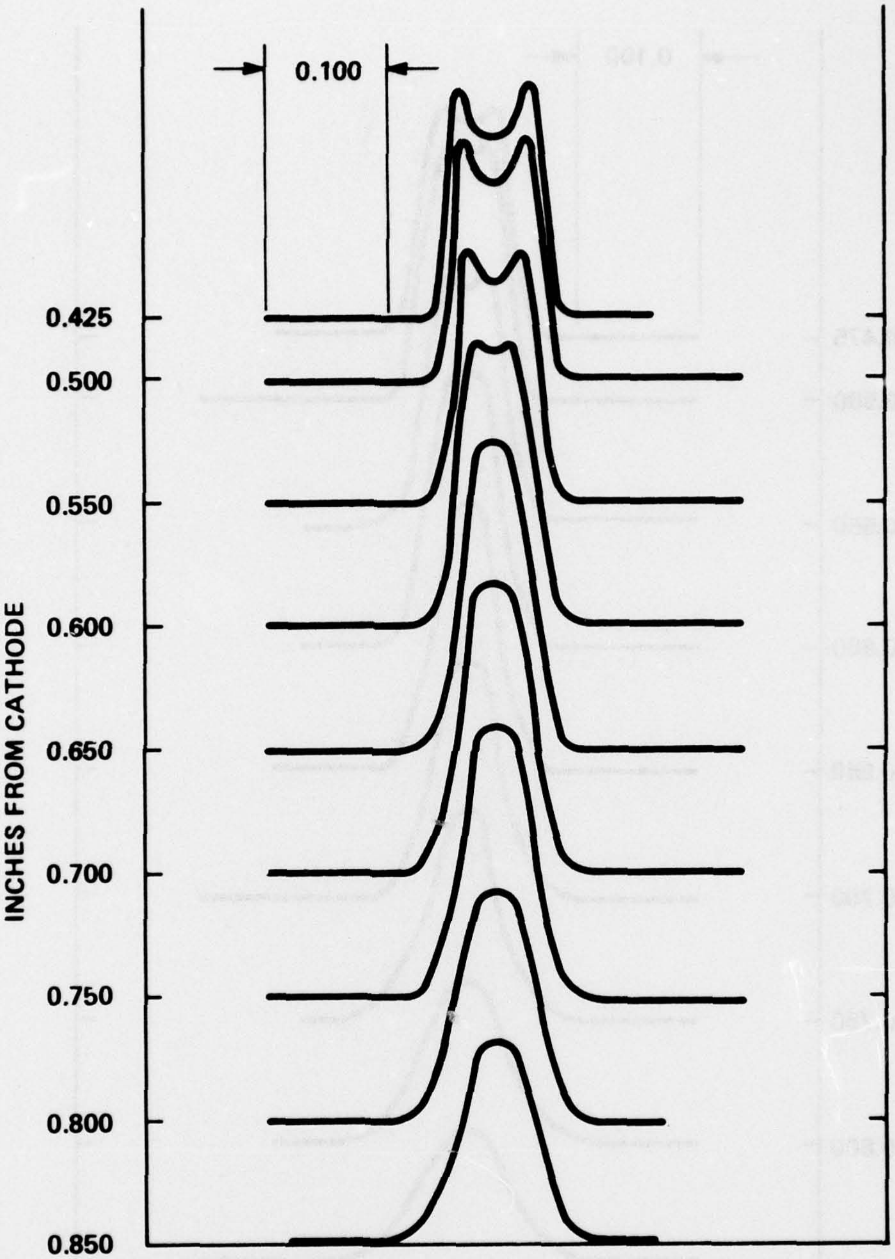

Figure 9. Beam Analyzer Result of Electrostatic Beam Low-Current Mode ($\mu k = 0.5$).

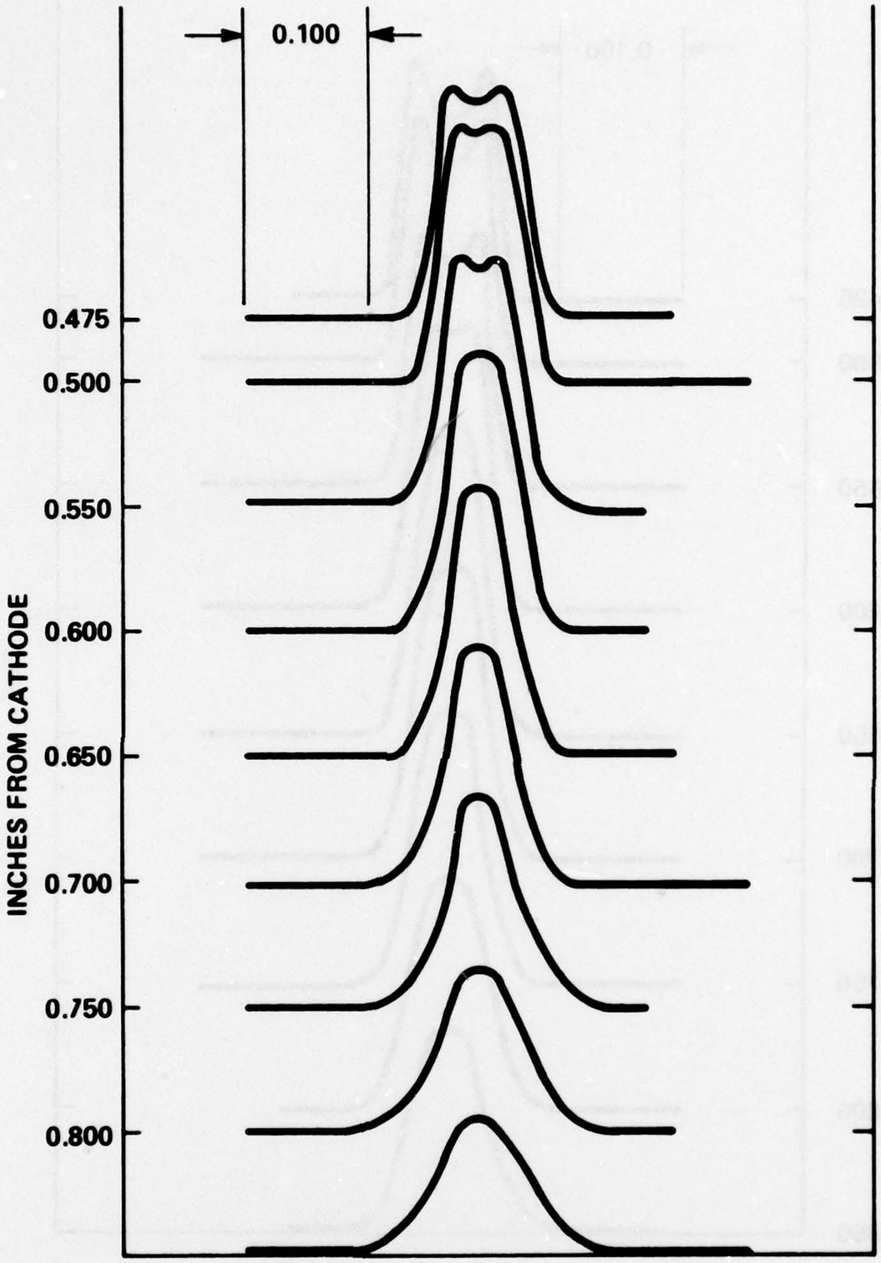

Figure 10. Beam Analyzer Result of Electrostatic Beam Low-Current Mode ($\mu k = 0.3$).

Table 1. Summary of Beam Data

Beam Condition	Beam Diameter		
	1.5 μK	0.5 μK	0.3 μK
Electrostatic	0.132	0.065	0.055
Confined Flow	0.136	0.126	0.122

6.2 EVALUATION OF THE GUN PRODUCING A HOLLOW LOW-CURRENT MODE BEAM

The first step in the hollow beam study was to analyze the beam in a solenoidal magnetic field. The stability and behavior of a hollow beam in solenoidal field is well known from several existing electron guns. This test was done to establish a standard for comparison with the PPM-focused beam.

The average beam diameter was 0.116 inch and the scalloping was 19%. The feasibility of maintaining a well-defined hollow beam with a magnetic focusing field of 1.3 times the brillouin field was confirmed. The hollow beam was well defined. The scalloping did improve when the magnetic field was raised.

The hollow beam was subsequently tested in a PPM field, where the effects of the rotational energy associated with the magnetic field reversal would be present. The beam was focused with a PPM field extending over 2.25 inches. The RMS value of the magnetic field was again 1.3 times the brillouin value required for the high current mode beam. The beam was again well defined, as can be seen in Figure 11. The average beam diameter was 0.129 inch and the scalloping was 15%. The average beam diameter was 0.105 inch. An evaluation of the hollow beam was also done for microperveance 0.3, which would correspond to a current pulse-up ratio of 5:1. This beam was well defined. The decrease in beam diameter due to the lower cathode current was negligible.

The third test was to probe the beam over the last two inches in a 13-inch PPM field. This was done to see how well the hollow beam was preserved after having traveled the length of a tube. The measured beam profiles are shown in Figure 12. The beam is still defined, although more scalloping and spiraling is evident from the beam behavior. The overall results from the evaluation of the hollow cw-mode beam is very encouraging. This type of gun is worth further investigation in the future.

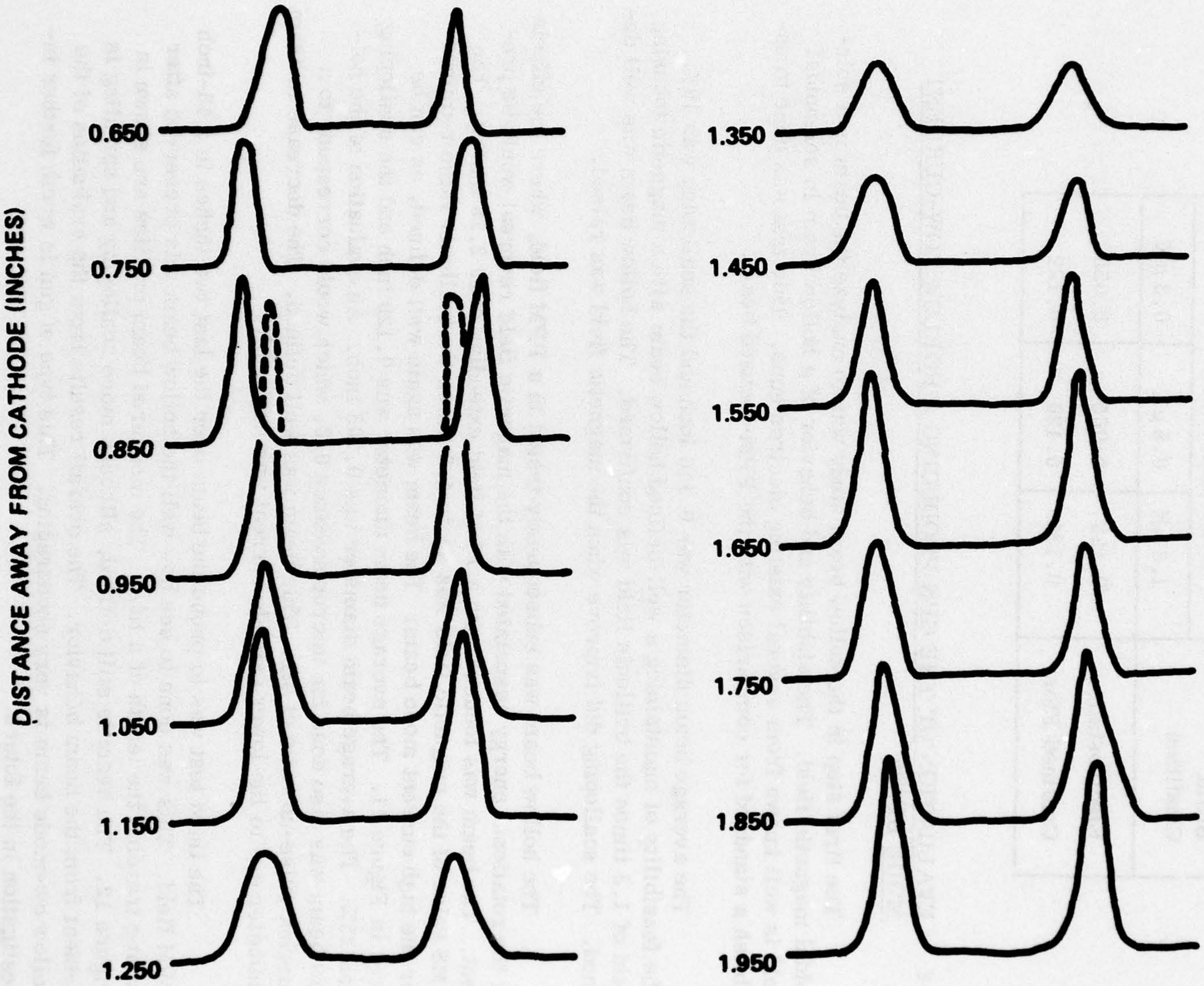

Figure 11. Hollow-beam Current Density Profiles in the PPM Focusing Field

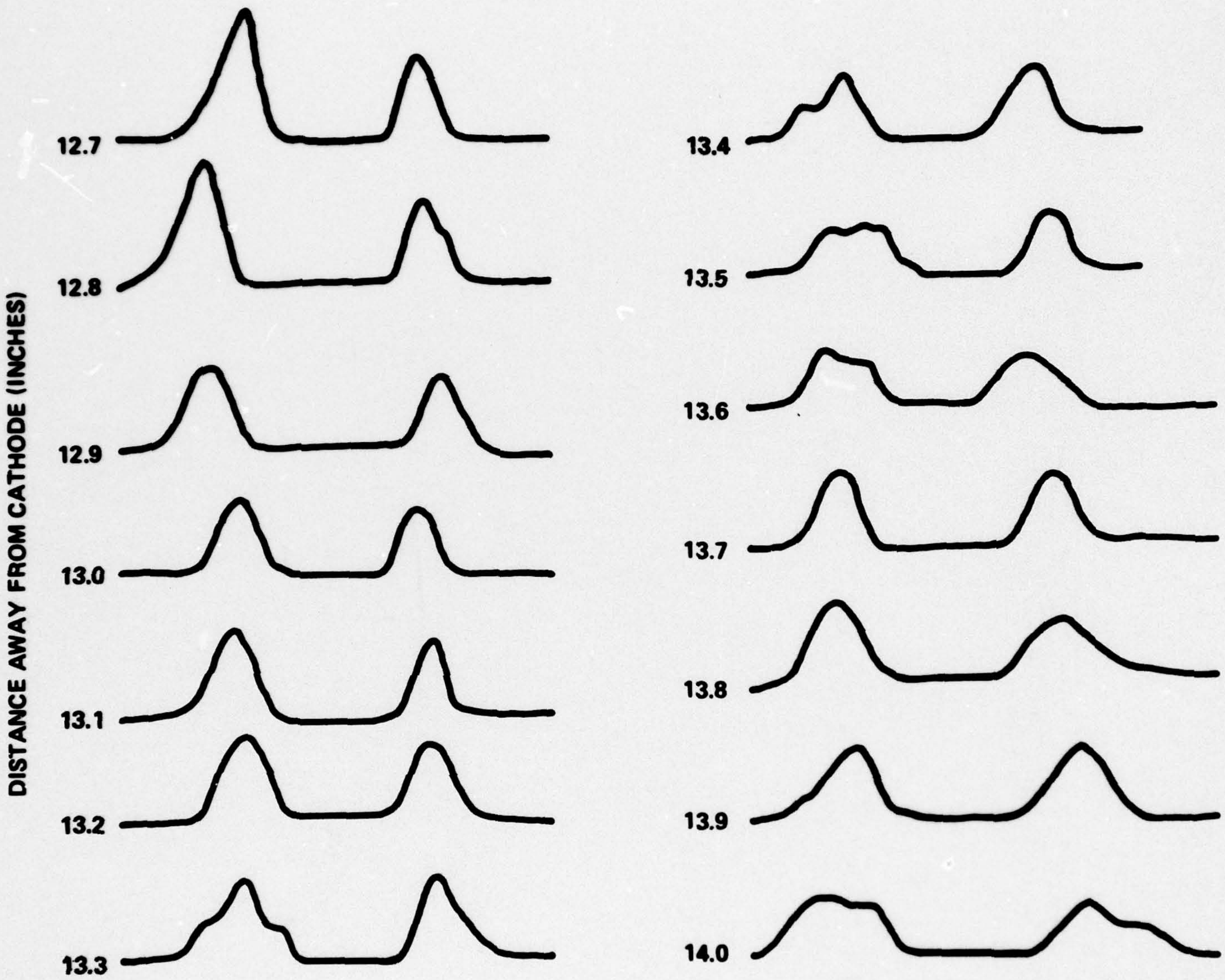

Figure 12. Hollow-beam Current Density Profile in the PPM Field at Collector End

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7. RF TEST

The circuit design for the tube was performed on R.A.D.C. Contract F 30602-76-C-0089. The object of that program was to develop an octave bandwidth dual-mode TWT with a 10:1 pulsed-to-cw power ratio. The tube employed resonant loss for BWO suppression and distributed loss for controlling small-signal gain ripple. U-shaped metallic channels were brazed to the ID of the tube body for velocity dispersion control. Figure 13 shows the circuit configuration.

The tube was operated at 7.5 kV for optimum rf performance over a microperveance range between 1.5 to 0.3. The gun study was performed at 9.0 kV. The reduction in the beam voltage required scaling down of the magnetic field to keep the beam diameter and the perveance constant. All of the rf test data were taken at 1% duty. After the magnetic focusing field was optimized the beam transmission under dc condition ranged from 96.0% to 94.0%. The transmission under rf saturated conditions ranged from 90.0% to 94.5%. The rf defocusing was minimal, the worst case was 4%. The tube performance data are shown in Figures 14 through 19.

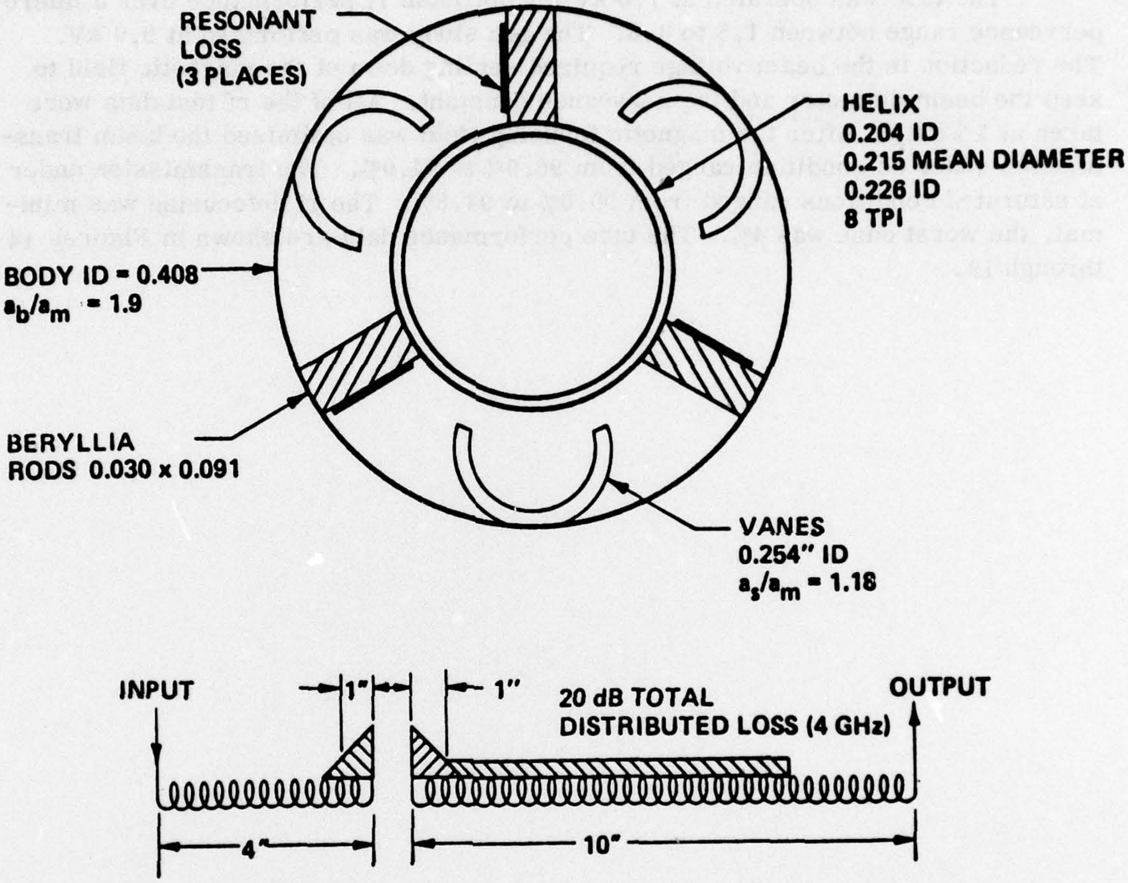
RESONANT
LOSS
(3 PLACES)
HELIX
0.204 ID
0.215 MEAN DIAMETER
0.226 ID
8 TPI
BODY ID = 0.408
a_b/a_m = 1.9
BERYLLIA
RODS 0.030 x 0.091
VANES
0.254" ID
a_s/a_m = 1.18
INPUT
1"
1"
20 dB TOTAL
DISTRIBUTED LOSS (4 GHz)
OUTPUT
4"
10"

Figure 13. Circuit Design for 10:1 Dual-Mode TWT

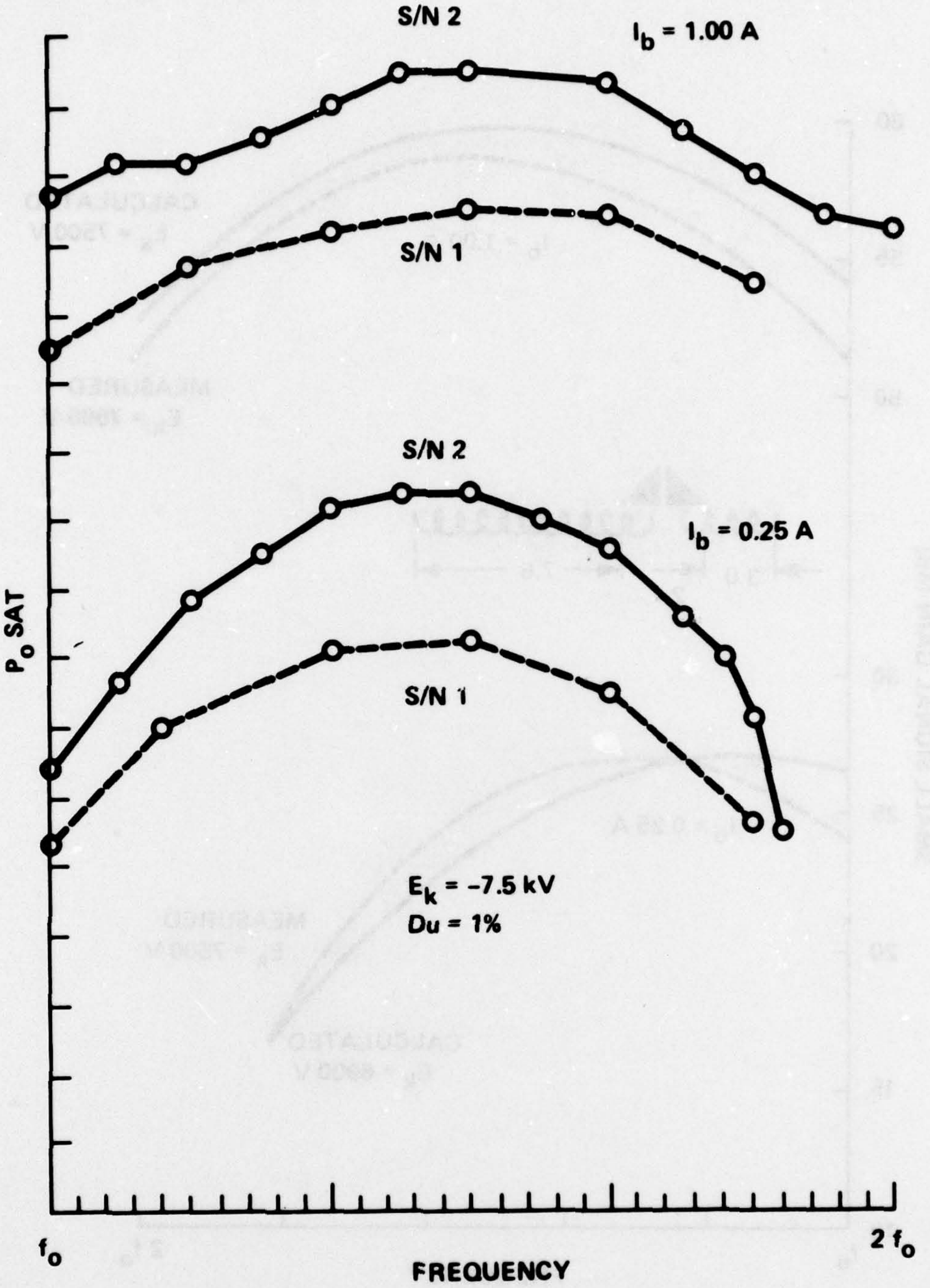

Figure 14. Saturated Output Power vs Frequency

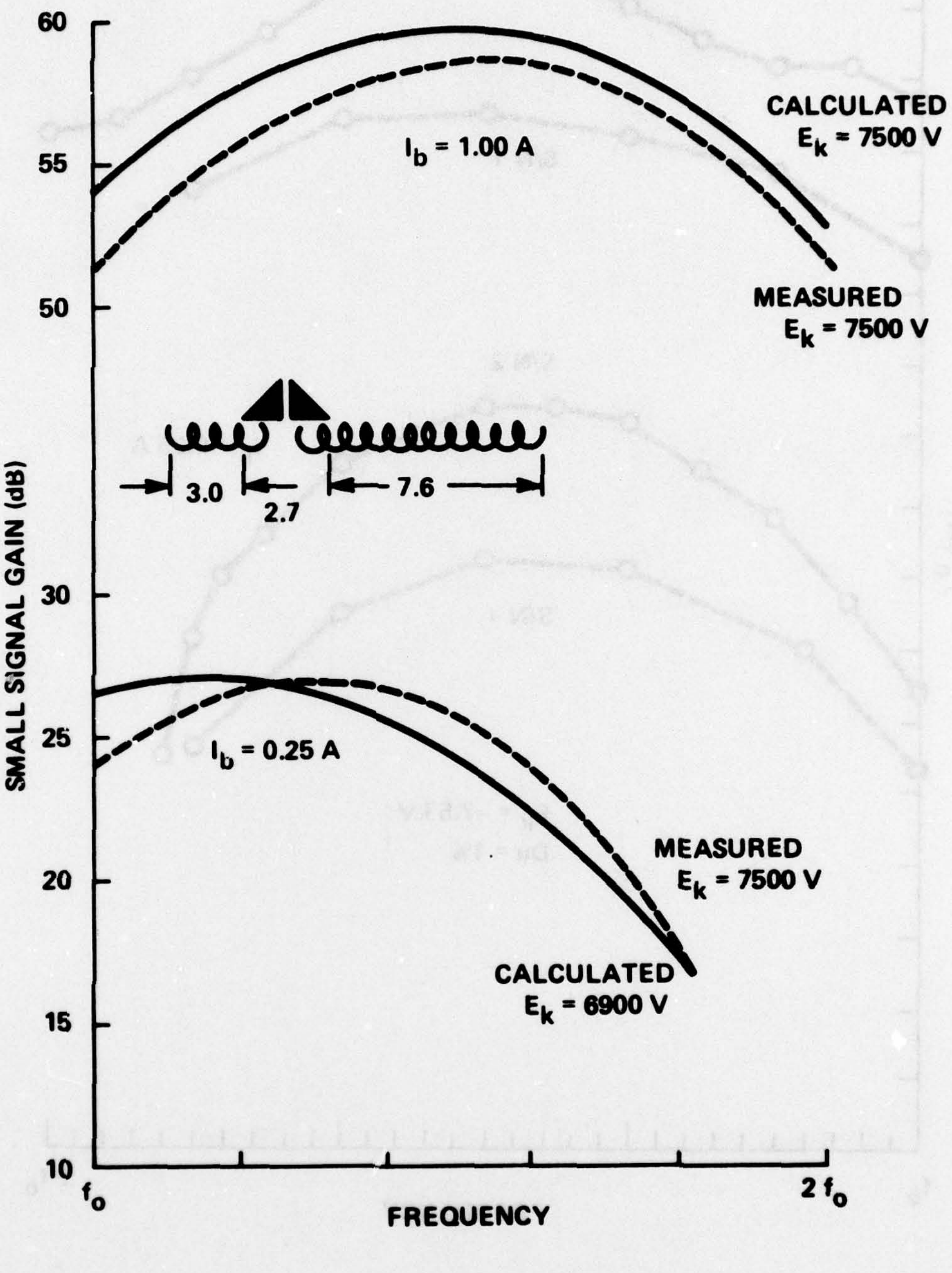

Figure 15. Comparison of Measured and Calculated Small Signal Gain

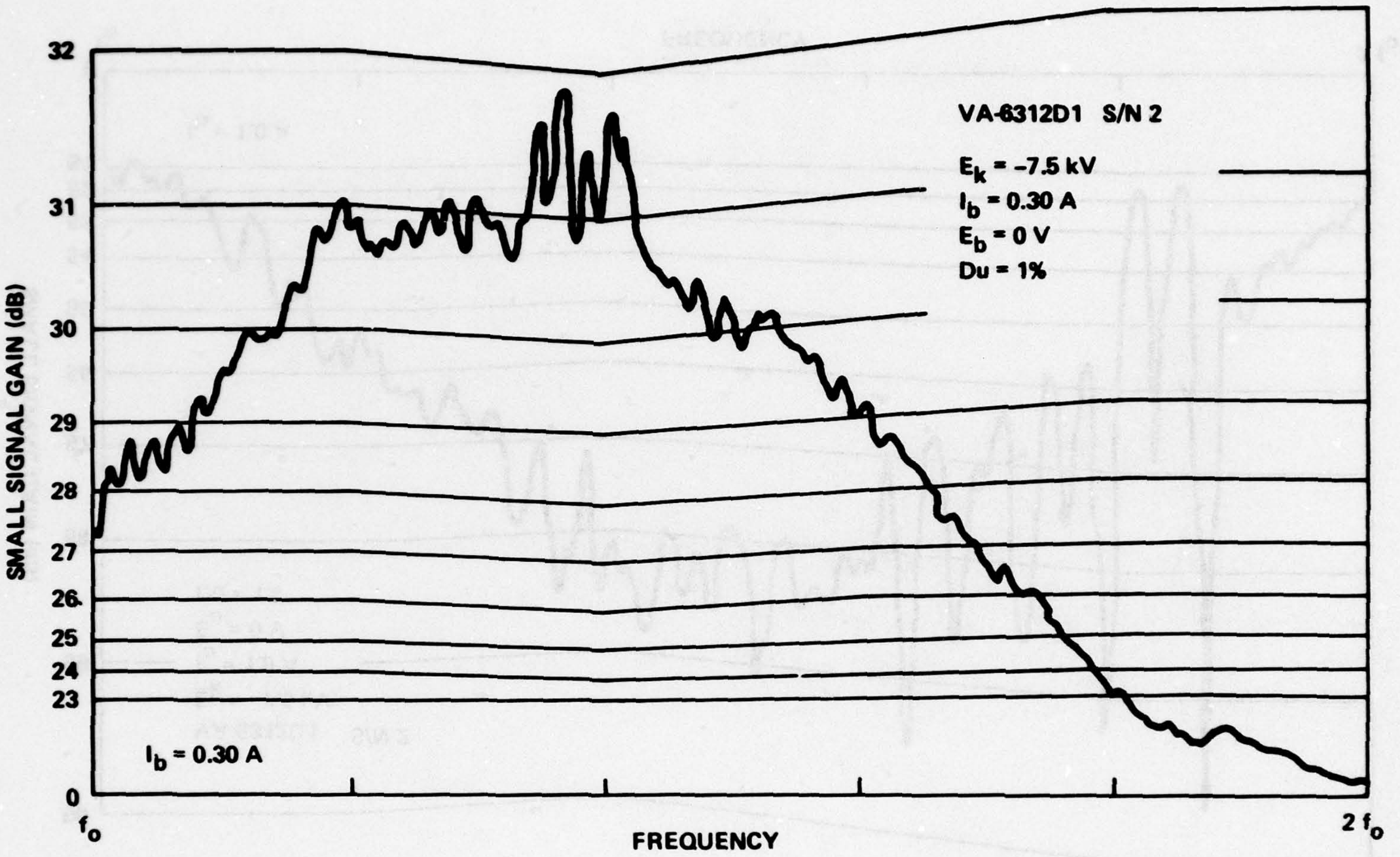

Figure 16. Small Signal Gain vs Frequency

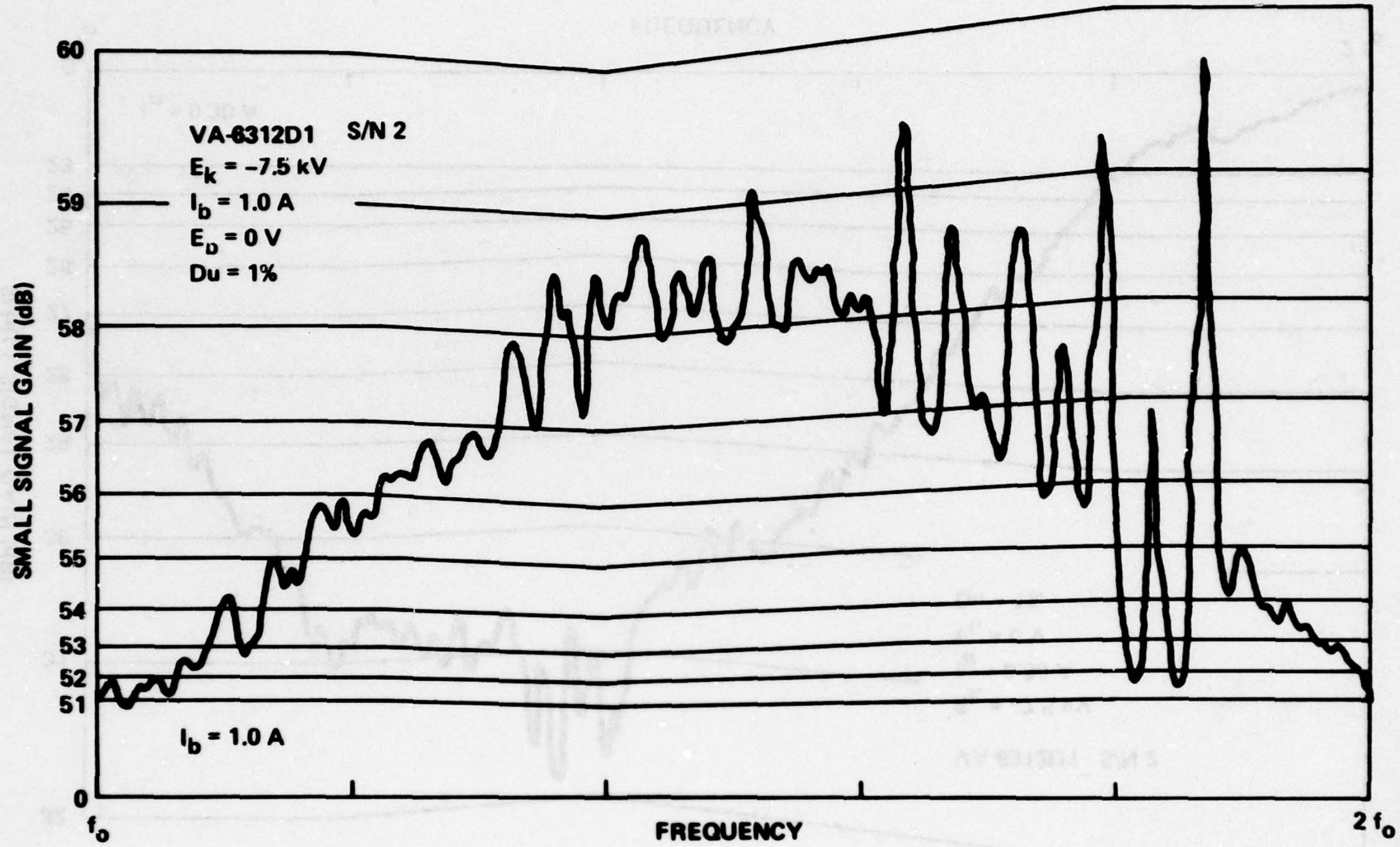

Figure 17. Small Signal Gain vs Frequency

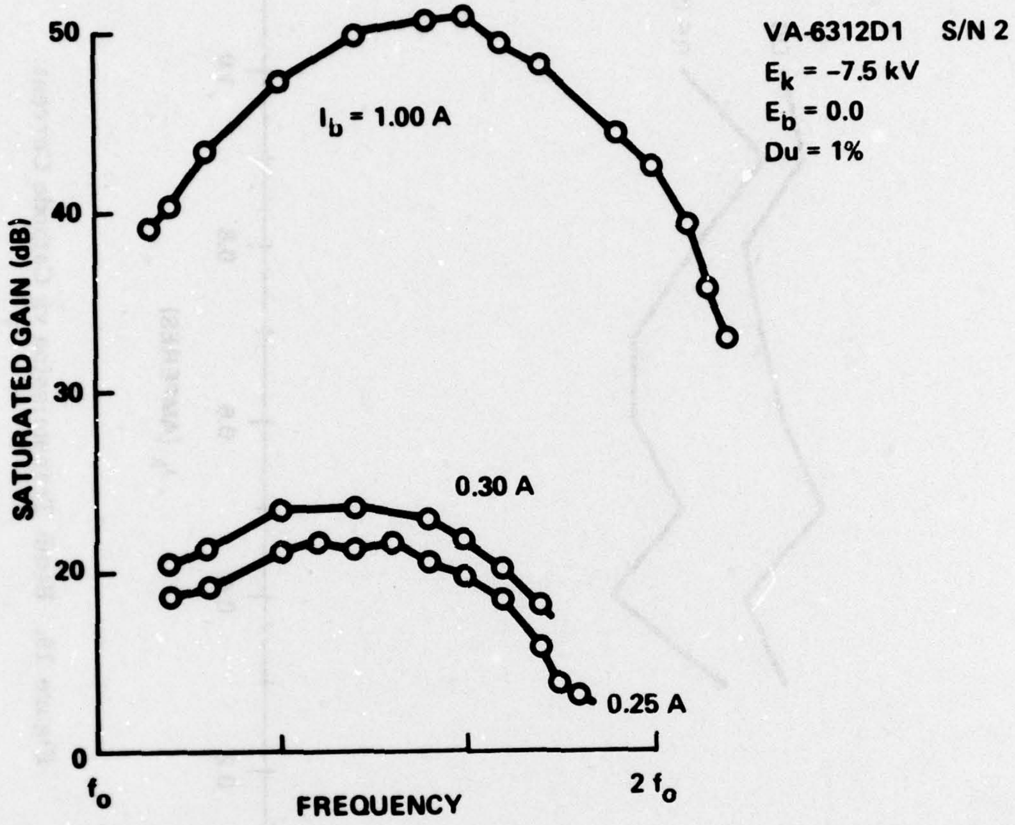

Figure 18. Saturated Gain vs Frequency

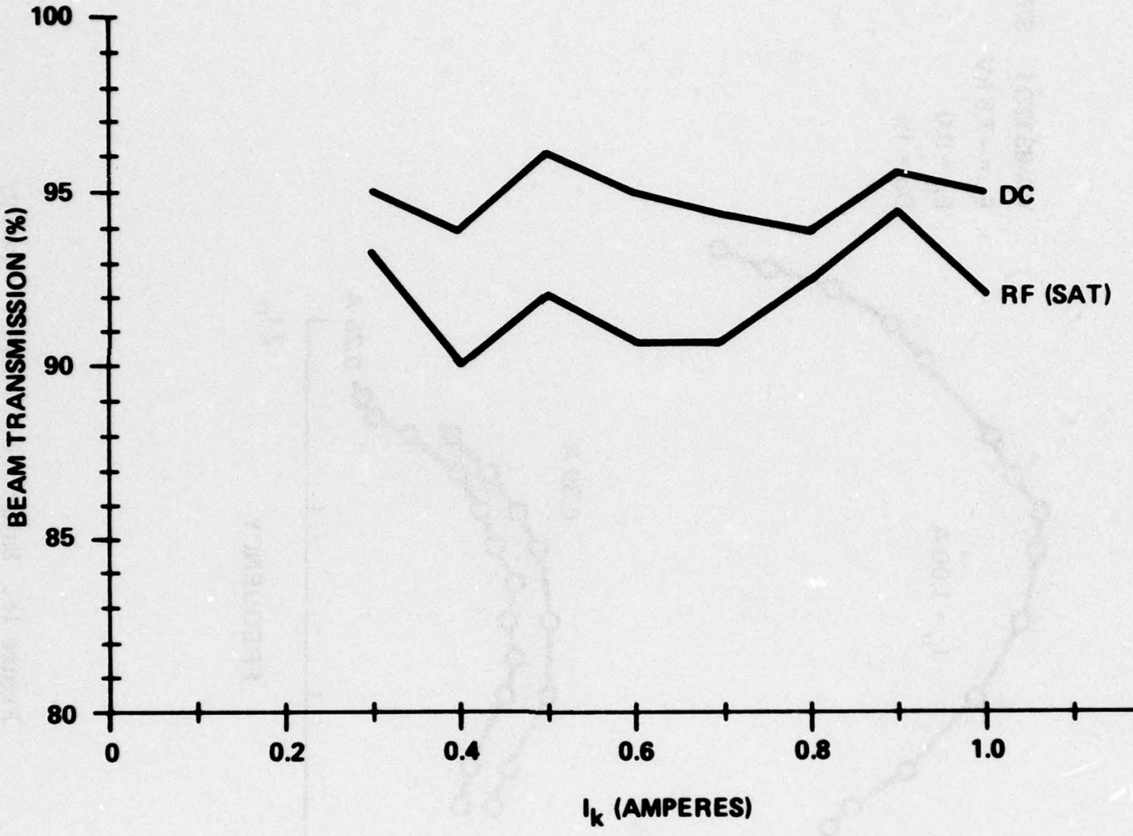

Figure 19. Beam Transmission vs Cathode Current

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